REPORT OF THE DIRECTOR OF THE FIXED NITROGEN RESEARCH LABORATORY.

SIR: I have the honor to transmit herewith the annual report of the Fixed Nitrogen Research Laboratory for the fiscal year ending June 30, 1923.

Respectfully,

F. G. COTTRELL, *Director.*

Hon. HENRY C. WALLACE,
Secretary of Agriculture.

INTRODUCTION.

The entrance of the United States into the World War brought forcibly to the attention of this Government its serious unpreparedness in the matter of nitrogen, particularly for explosives. Other countries, with the exception of the Central Powers, had found themselves in a similar situation, and the universal rush to erect and place in operation plants for the fixation of atmospheric nitrogen is now a familiar story. The years following the war have added a chapter of no less interest, for they have seen the nations of the earth awakening to a realization that their peace-time requirements of nitrogen must come in increasingly greater proportion from sources other than the natural deposits. Thus, the past year has seen Germany operating fixation plants, the output of which has rendered her almost entirely independent of outside sources, and it is predicted that in the next few years she will be exporting large quantities of nitrogenous fertilizers. The growth of this industry in Germany can best be appreciated when it is pointed out that in 1910 Germany imported over 65 per cent of the nitrogen she consumed.

Although Germany has by far outstripped other countries in producing fixed nitrogen, many of the latter are making progress. This is most clearly shown by the fact that in 1920 more than 36 per cent of the world's production was supplied by the fixation of atmospheric nitrogen, having risen from little over 1 per cent in 10 years.

In the peace-time development of actual producing plants for nitrogen fixation this country has taken practically no part, less than 1 per cent of our present requirements being supplied by the fixation of atmospheric nitrogen within our borders. Meanwhile, the rapid growth in the use of fertilizers in the United States is repeating what has taken place in Europe. As the population increases, larger yields per acre become necessary. One way of accomplishing this is by the use of commercial fertilizers.

The present consumption of nitrogen in fertilizers in the United States is about 200,000 tons per annum. The capacity of the Government plant at Muscle Shoals, now idle, is 40,000 tons per annum. From 1899 to 1914 the consumption of fertilizer in the country practically tripled; i. e., an average rate of increase of $7\frac{1}{2}$ per cent a year. The rate of increase during the last five years of this period was even greater. Since the slump in 1915 and 1916 further comparisons have been difficult, owing to the disturbed economic conditions throughout the world.

If the price of fertilizer were low enough, there is for practical purposes almost no limit to the amount that could be advantageously used as our people come to understand its use and importance. It has been estimated by Dr. Jacob Lipman, director of the New Jersey Agricultural Experiment Station, that the annual loss of nitrogen from all land under cultivation in the United States which is not replaced by manure, by the nitrogen supplied by plowing under leguminous crops, by atmospheric precipitation in the form of rain and snow, and by the present use of commercial fertilizer amounts to between 3,000,000 and 4,000,000 tons of nitrogen. To replace all of this would take from 15,000,000 to 20,000,000 tons of sulphate of ammonia, or from 150,000,000 to 200,000,000 tons of ordinary commercial mixed fertilizer.

It would not now nor in the immediate future be expedient to use fertilizer to any such extent on all of the land under cultivation, but these figures suggest at least an upper limit to the use of nitrogen in fertilizer, and show how far from that limit the present consumption is.

No large nitrogen-fixation industry exists in this country to-day. Our requirements for nitrogen are ever increasing, and these facts make it imperative that we have a thorough knowledge of all processes now in operation and vigorously prosecute research to keep us abreast of developments.

ESTABLISHMENT OF THE LABORATORY.

After the armistice was signed, the Fixed Nitrogen Research Laboratory was established by the Secretary of War (March 29, 1919) in order to coordinate the knowledge which had been obtained concerning nitrogen fixation by the War Department during the war, to obtain further information necessary for the peace-time utilization of the Government nitrate plants at Sheffield and Muscle Shoals, Ala., and to study in general the fixation and utilization of nitrogen. On July 1, 1921, the Fixed Nitrogen Research Laboratory was transferred by Executive order to the United States Department of Agriculture. For the fiscal year July 1, 1922, to June 30, 1923, the laboratory began operation with a budget of $264,000. Economies in personnel, purchases, etc., reduced the actual expenditure to $217,000. Authority for this work is contained in the national defense act of June 3, 1916, specifically authorizing the President to " * * * cause to be made such investigations as in his judgment are necessary to determine the best, cheapest, and most available means for the production of nitrates and other products for munitions of war and useful in the manufacture of fertilizers and other useful products by water power or any other power."

Processes may conveniently be recognized as naturally falling into three categories, viz: (1) Processes which have attained a position of industrial importance, but from intrinsic limitations are apparently already past their zenith and doomed to displacement by more economical processes. (2) Processes already closely competing with those of class 1 and which present manifest opportunities for further fundamental improvements looking to cost reduction. (3) Processes not yet industrially competing with class 2, but out of which it seems possible that something still better may ultimately come. Of course, we must not expect to fit any particular process too exactly into the above classification; also, processes totally unsuited to the bulk of industrial production may prove the key to important special situations.

At the time of our entry into the war the three processes of nitrogen fixation claiming most attention for Government-built plants were the electric arc, the cyanamide, and the direct synthetic ammonia (Haber). Of these, the arc was quickly placed in class 1 on account of its very high power requirement.

The cyanamide process, which had definitely crowded the arc process out of class 2 because of the former's threefold greater energy, economy, and adaptability of products, was already recognized to have reached its probable limiting efficiency.

Even at that time there was much to indicate that the direct synthetic ammonia process, which was already operating on a commercial scale in Germany, would eventually displace the cyanamide process, just as this had displaced the arc process, and primarily for the same reason, viz, its smaller power requirements. The direct synthetic ammonia process was, however, still very new and wholly untried on a commercial scale outside of Germany. For this reason it was decided to put the main reliance for war purposes in the cyanamide process, which, though intrinsically more expensive on account of its larger power requirements, could be installed with absolute certainty of its working smoothly from the start, which could not be said at that time for the direct synthetic ammonia process, due to the more intricate character of its equipment and our lack of knowledge and experience concerning it.

CYANAMIDE.

During the first two years, while the laboratory was still under the War Department and it was felt that the cyanamide plant at Muscle Shoals might at any time be called upon to start up under Government operation, the laboratory's attention was naturally directed largely to problems connected with the peace-time operation and possible improvement of the cyanamide process. These studies, while furnishing valuable data against the time of possible further operation of the large plant, have also confirmed the idea that the best chances for making further decisive cuts in the cost of nitrogen for fertilizer purposes lie along the lines of other processes.

During the past fiscal year additional data have been secured on the stability of calcium carbide at high temperatures, and upon the mechanism of the nitrification of carbide. In connection with this work a very accurate method for the determination of calcium carbide has been developed.

In addition to the study of the cyanamide process itself, the laboratory has also studied various products which may be made from cyanamide, such as dicyanodiamide, melamine, guanylurea, guanidine, and related compounds. During the past year our studies on cyanamide derivatives have been largely directed toward a summarization of the relationships existing between the various compounds in the series and analytical methods for their accurate determination. The results obtained should simplify to a considerable extent the problems of research in this field. Methods have been developed for preparing the ethyl ester of guanidine carboxylic acid, guanidine carbonate, and urethane. Some of the large number of cyanamide derivatives have already found distinct uses in the manufacture of military explosives, in medicine, and in the arts.

This class of compounds forms the natural starting point for a whole new field in chemistry, much as certain coal-tar compounds lay at the base of the present dyestuff industry. The sources of these compounds heretofore available have made them too expensive to be considered for wide uses, and the industrial aspect of this field in chemistry has therefore been slow of development. Now that the necessary raw materials can be obtained cheaply and in large quantities through cyanamide, this group of compounds presents a very attractive opportunity for industrial chemical research and development.

While it is not at all likely that the amount of nitrogen going into such products would ever approach the tonnage absorbed by the fertilizer industry, the aggregate value of the products might not be so disproportionate. So that while the fertilizer industry may draw its nitrogen supply in increasingly greater proportion from sources other than cyanamide, the latter may still have an important mission to perform in supplying the basis for these more specialized compounds.

The laboratory has made quite definite contributions to the chemistry of these cyanamide derivatives; but having thus opened the way and connected the subject with its other more basic work on the actual fixation of nitrogen, it is felt that further developments in this line may now very properly be left for the greater part at least to the research laboratories of the universities and the industries.

In experiments on the actual use of fertilizers, the laboratory has cooperated with the Bureau of Plant Industry. During the year a bulletin under joint authorship has been prepared and is now in press (United States Department of Agriculture Bulletin 1180) covering the results of field work for several years past on the comparison of the effects of cyanamide and various other forms of fixed nitrogen on different crops under a variety of conditions. One of the most promising developments of the work is the use of mixtures of cyanamide with neutral or basic phosphates. It had come to be generally assumed that about 60 pounds of cyanamide per ton of mixed fertilizer was an upper limit of good standard practice. This was based, however, almost entirely on experience with mixtures containing acid phosphate, which at present is used almost exclusively in this country. Experiments detailed in the forthcoming bulletin and which are being further checked and extended in the field seem to indicate that in the case of certain crops at least, notably corn, when acid phosphate is replaced by neutral or basic phosphates, such as calcined

phosphate rock or Thomas slag, a very much greater cyanamide content may be used safely and effectively.

If further work substantiates these indications, the results may be of very considerable importance in finding an outlet for the product of the cyanamide plant at Muscle Shoals, since the difference in cost of manufacture, even for a part of the product, as between cyanamide and ammonium salts may mean the difference between profit and loss.

CYANIDES.

In addition to the cyanamide and direct synthetic ammonia plants near Muscle Shoals, the Government also, during the war, commenced the construction at Saltville, Va., of a plant for the fixation of nitrogen as sodium cyanide (Bücher process). Considerable difficulties were met with, and, although some cyanide was produced, the plant did not reach commercial operation before the armistice, shortly after which it was dismantled. When this process and plant were first considered it was thought by some that it might be possible thereby to pass from free nitrogen through cyanide to ammonia at a lower cost than through cyanamide, and even failing in this it would still be a cheaper process for reaching the cyanides and hydrocyanic acid.

By the time the construction of the Saltville plant was definitely started, however, the problem had narrowed down to simply producing cyanides for the needs of the Chemical Warfare Service, but the work at this plant by no means exhausted the experimental possibilities for the use of the reactions involved, nor did it furnish us with the fundamental knowledge of the exact mechanism of these reactions. The alkali cyanide reactions have the advantage over those of calcium cyanamide that they do not require electric-furnace temperatures, nor so great a power consumption, but they are incomplete, and the volatility of the substances introduces other complications. The laboratory work on these cyanide reactions which was originally laid out has during the past year been nearly covered, and it is hoped to complete this and publish the data secured during this coming year. In the meantime, one commercial company has established a plant in California and is manufacturing hydrocyanic acid, largely for fumigation of fruit trees. The work at the Fixed Nitrogen Research Laboratory has not furnished us with any particular encouragement for obtaining fixed nitrogen at fertilizer prices through any cyanide process operated primarily as such. There is, however, still the chance that these reactions, when occurring incidentally in other processes, particularly in the iron blast furnace, may, if proper advantage can be taken of them, be made to furnish crude cyanides as by-products at a low enough cost to permit of making ammonia for fertilizer.

It has been known for many years that in certain parts of the blast furnace considerable amounts of cyanides are formed by the alkalies and carbon in the charge taking up nitrogen from the blast, but in the normal running of the furnace these are volatilized and swept upward by the blast into zones of oxidation, where they are reoxidized to carbonates, thus again liberating the nitrogen. The idea of drawing off this material before it undergoes oxidation has long been suggested and even patented, but still awaits thorough large-scale experimentation and development. It happens to be a type of problem on

which decisive information can hardly be secured on a laboratory scale. Blast-furnace operations have to be on so large, continuous, and expensive a scale that it is difficult to find anyone willing and in position to undertake or permit experiments of this type on an operating furnace. However, it is now hoped that during the coming year such an opportunity may present itself through cooperation with the Bureau of Mines and the industry.

DIRECT SYNTHETIC AMMONIA PROCESS.

One of the major problems of the laboratory has been the study of the direct synthetic ammonia process, frequently designated as the Haber process. An exhaustive study of this process was undertaken for two reasons:

1. The United States nitrate plant No. 1 was designed to operate in accordance with this process. In the test made on this plant it was found that successful operation was not likely until the chemical and engineering problems involved were more thoroughly understood.

2. The direct synthetic ammonia process is at present generally considered to be one of the most promising, if not the most promising, method for fixing atmospheric nitrogen. Although the chemical and engineering difficulties are serious, the process undoubtedly presents great possibilities for the lowering of costs. Therefore, irrespective of the immediate needs of the Government plant at Sheffield, the investigation of this process would still have occupied a large part of the research program of this laboratory.

The problems involved in the synthetic ammonia process may be divided into two groups, first, those which concern the process for making hydrogen combine with the nitrogen of the air to form ammonia, and, second, those which concern the process for manufacturing and purifying the hydrogen-nitrogen mixture employed in this synthesis.

The principal problem of the first group centers about the catalyst. In fact, the nature of the entire process is largely dependent upon its characteristics. For example, the properties of the catalyst determine what the purity of the hydrogen-nitrogen mixture must be. Since the purification of the gas represents a very large item in the cost of making ammonia by the process as employed at Sheffield, the importance of the catalyst is not to be underestimated.

Furthermore, the properties of the catalyst determine such factors as size of the catalyst chambers, the circulating system, and the heat interchangers. The nature of the apparatus for removing the ammonia formed also depends in large part upon the activity of the catalyst. With a poor catalyst the efficient removal of the ammonia becomes a very serious problem. The temperature at which the catalyst gives the greatest yield of ammonia is also an important consideration in the design and construction of the catalyst chambers. Briefly, we may say that every portion of the synthesis equipment is subject to modification as the character of the catalyst is changed.

Probably the greatest single contribution of this laboratory to date is the development of a very reactive and stable catalyst. As far as we have been able to learn, there is no country in the world which has an ammonia catalyst superior to that developed by this laboratory. A method has also been developed for manufacturing this material

which gives the necessary chemical control of the product and at the same time makes large-scale production possible. As a consequence, we are now in possession of such reliable information concerning at least one type of ammonia catalyst and its manufacture that one of the principal obstacles to the successful operation of such plants as United States nitrate plant No. 1 at Sheffield, Ala., has been removed.

There is still, of course, the possibility that a much more reactive catalyst may be found. As a consequence, this laboratory has continued during the past year its study of this phase of the problem. Before any marked improvement over the present catalyzers can be effected there must be a much better understanding of the way in which the catalyzer makes hydrogen combine with the nitrogen. Consequently, an extensive study of the mechanism of the reaction has been in progress. It is hoped that the results of this work may soon be published.

Although it is not too much to expect that painstaking research may reveal catalyst materials much more active than those which we have now discovered, it is felt that the greatest advances in the direct synthetic ammonia process within the near future may lie in the direction of increased pressures. Contrary to popular belief, there is nothing inherently impracticable in carrying out the synthesis of ammonia at pressures considerably in excess of those employed at Sheffield. During the past year tests have been made at various pressures up to 1,000 atmospheres. In these tests the activity and the longevity of the catalyst have been most satisfactory. From a chemical viewpoint there are many advantages to be gained by high-pressure operation, and when the engineering problems which arise at higher pressures have been solved there is the possibility that capital and operating costs can be very substantially decreased.

During the past year most of the demands for information concerning the synthetic ammonia process have come from groups particularly interested in the production of liquid ammonia from by-product or waste hydrogen. Liquid ammonia commands a price which makes the operation of small units (say 1 ton per day) commercially feasible. Much of the engineering research on the process during the past year has had in mind the special requirements of these small producers. While the amount of their product is insignificant compared to total national production, they would perform a highly important function in spreading knowledge and experience concerning the art in this country. As a result of this work we believe that the laboratory is now able to offer considerable assistance in the design of 1-ton plants.

The primary interest of the laboratory has been, however, the much larger problem of reducing the cost of fixed nitrogen suitable for fertilizer purposes. This study has involved a consideration of the advantages and disadvantages of operation at various pressures. The principal pressures suggested by the proponents of different systems for commercial operation have been 100, 200, 300, 600, and 1,000 atmospheres. Since the details of the process are determined in part by the pressure at which the process is operated, naturally the cost of producing ammonia may be expected to vary somewhat as the pressure conditions are changed. In making an analysis of the possibilities of operation at these various pressures, the laboratory has been considerably handicapped because of its inability to

obtain information concerning all the factors which enter into the cost of production. With its present facilities such items as labor and repairs can not be determined with certainty.

Much more rapid progress could be made if a large-scale plant were available in connection with whose operation varying pressure conditions could be studied. From the results of such a comparative study it would be possible to select a set of conditions which are best suited to the industrial conditions peculiar to the United States.

A project involving the examination of 25 alloy steels reached completion during the past year. In this test alloy steels suitable for the high-pressure, high-temperature synthetic ammonia reaction were exposed for about one year to a nitrogen-hydrogen-ammonia mixture at 500° C. and 100 atmospheres' pressure. As a result of this test an alloy steel suitable for use at 100 and possibly up to 300 atmospheres can now be recommended.

The investigation of methods for removing ammonia from the high-pressure circulating system of the direct synthetic ammonia process has been under investigation at this laboratory by the Bureau of Soils. This investigation was primarily designed to meet the particular needs of the Government plant at Sheffield. This project was completed during the year, and the results will soon be available.

Although the production of an efficient and dependable catalyzer was the necessary first step and key to the whole problem of synthetic ammonia, now that this has been accomplished the next and greatest opportunity for reducing cost of ammonia production lies in the manufacture of the pure hydrogen consumed in the process. At present the cost of hydrogen and its purification before it can be combined with nitrogen by the catalyzer represents about two-thirds the cost of the ammonia produced.

Three main roads for production of hydrogen are open to us: Electrolysis of aqueous solutions, decomposition of hydrocarbonaceous materials, and the reduction of water vapor directly or indirectly by carbon.

The electrolysis of aqueous solutions is a simple and well-established process already worked out nearly to its theoretically highest possible efficiency and produces hydrogen needing little further purification, but the consumption of electric energy is so great that it can only be considered where either (a) the main purpose of the electrolysis is to obtain some other valuable product, such as oxygen or caustic soda, and the hydrogen is thus a by-product, or (b) where electric power is exceedingly cheap. The total possibilities under (a) are small compared with the nitrogen industry and are widely scattered in small units. Those under (b) can only be considered as transitory for each individual case, because wherever electric power is developed in large quantity it immediately begins to build up its own market and its value inevitably and automatically rises.

Thus while the electrolytic process for hydrogen should be very useful in the present introductory stages of the synthetic ammonia process it must on the large scale eventually give place to purely chemical methods of preparation, which, though only closely competing with it at present, have intrinsically greater possibilities for improvement and thus for ultimate reduction of cost.

Through the chemical reactions of coal, coke, petroleum, or natural gas, either by themselves or with water vapor, crude hydrogen may

be prepared at a small fraction of its cost by the electrolytic method, but at present the cost of purification absorbs most of the saving over the electrolytic process. However, it is just in these purification processes that there appears to be the greatest chance for improvements, and thus for reducing the cost of the ultimate product, fertilizers. It is on this account that it is proposed in the coming year to center so large a proportion of the laboratory's efforts upon this problem of pure hydrogen production.

One of the methods already investigated was the cracking or decomposing of hydrocarbons, especially natural gas. Where large quantities of natural gas are going to waste, conversion of the gas into ammonia may be considered a conservation of our resources quite worth while, besides offering the possibility of cheap ammonia. The chief difficulty in this method lies not so much in the chemical and engineering aspect of the problem as in the uncertainty of the gas supply. If a plant could be assured of a continuous supply of natural gas for a number of years this might be a promising method for obtaining hydrogen and in turn ammonia.

The gases from the by-product coke ovens of this country contain many times the amount of free hydrogen required to fix all the nitrogen now consumed in fertilizers, but here again there is need for careful study of methods for separation and purification. This is another problem to which the laboratory is devoting its attention.

When hydrogen is made through the reduction of water vapor by coke in a gas producer, as was planned at Sheffield, the principal chemical problems are concerned with the conversion of carbon monoxide and steam to hydrogen and proper purification of the gas mixture before it can be used in the synthesis. These problems have been under study for some time by the laboratory, and already definite results have been obtained which will be of material assistance in operating such a plant as that at Sheffield.

During the past year a catalyst for converting carbon monoxide and steam into hydrogen was studied, which on a laboratory scale shows considerable promise. The efficiency of the catalyst for converting carbon monoxide and steam into hydrogen determines in part the nature of the final purification which can be employed. The removal of uncombined carbon monoxide by means of cuprous ammonium carbonate or formate solutions has been studied and the results have been published. The possibility of converting carbon monoxide into methane has also been investigated and catalysts suitable for this reaction have been studied.

ARC PROCESS.

Concerning the electric-arc process for nitrogen fixation, this was the first to be commercially developed, due to its simplicity, but its excessive power consumption doomed it from the start in competition with the cyanamide and still more with the direct synthetic ammonia process. Another almost equally serious drawback to its peace-time competition is that it leads directly to nitric acid instead of ammonia, and this is less easily and cheaply converted into stable, dry fertilizer ingredients suited to our present methods of application. The possible importance of the arc process for military emergencies should, however, not be overlooked, as in this case a large amount of the

nitrogen is wanted in the form of nitric acid, and where power is available the simplicity of the arc furnaces makes the rapid installation of a large battery of them relatively easy. The cumbersome and expensive part of the arc installation has always been the large stone towers for absorbing in water the gases after leaving the furnaces. On this part of the process, however, there seems excellent opportunity for radical improvement, and during the past year this laboratory has made decided progress in this direction, especially on the use of solid adsorbents for the preliminary concentration of the active gases. The same procedure is also applicable in the manufacture of nitric acid by the oxidation of ammonia. This line of investigation is being actively continued and the results thus far obtained are being prepared for publication.

ELECTRIC DISCHARGE IN GASES.

While there at present seems little hope of greatly reducing the consumption of electric power in the arc process proper, the study of electric discharge in nitrogen both by itself and mixed with other gases under a wide range of pressure and other conditions presents an extremely promising field for investigation which the laboratory is energetically developing. Aside from the possibility that out of such investigations may eventually come knowledge enabling us to more efficiently apply the electric current to the direct fixation of nitrogen, even greater importance is attached to this work because of the light it may throw upon the ultimate structure and chemical properties of the atoms and molecules here involved. In the present state of development of the art it would seem primarily through such knowledge as this that further fundamental improvements in any of the processes of nitrogen fixation can most confidently be looked for. This forms an extension of the work on ozone and active nitrogen mentioned in last year's report. Particularly significant is the progress made this past year in regard to the properties and behavior of active nitrogen which is formed when powerful electric discharges are passed through pure nitrogen at low pressure. Under these conditions the nitrogen after leaving the path of the discharge continues to glow for an appreciable time and reacts readily with many substances toward which ordinary nitrogen is quite inert.

In the arc process as commercially practiced, electrical, thermal, and photochemical phenomena are so closely intertwined as to be indistinguishable. The electrical investigations of the laboratory just referred to aim, among other things, at isolating and studying the electrical and photochemical parts of these phenomena.

THERMAL PROCESSES.

On the other hand, the study of the purely thermal aspect of the phenomena occurring in the arc is also of great importance. This has found its practical expression, for instance, in the Haüser process, by which a certain amount of nitric acid was made by the Germans during the war. In this process the heat of explosion of a mixture of air and coal gas replaces that of the electric arc. If working under this principle it should prove possible to combine even a moderate recovery of both power and the oxides of nitrogen, it is easy to imagine important developments ultimately in this direction. The laboratory has as yet devoted very little detailed

study to this phase of the general problem, partly because its adequate study involves a very considerable excursion into the theory and practice of internal-combustion motors. The strengthening of our engineering division this year will greatly facilitate the handling of such problems.

NITRIDES.

The fixation of nitrogen in the form of various nitrides has also occupied the attention of the laboratory this past year, but as yet nothing very definite has developed to indicate that this field holds out especial promise from the standpoint of self-contained fixation processes. The best immediate chances here would seem to lie in the possibility of combining nitrogen fixation with the preparation of some other valuable product; e. g., some of the modifications of the Serpek process, where the formation of aluminum nitride serves not only as a step toward fixing atmospheric nitrogen as ammonia, but also to prepare pure alumina from crude ore and possibly even admit of using as ore material not now considered available, such as bauxites running too high in iron for present processes.

NITROGEN FIXATION BY ORGANISMS.

Nature's own most important channel for fixing atmospheric nitrogen and storing it up in our soils is undoubtedly the action of certain living organisms of which several species of bacteria are the best known. Much has been done both in the study of the best field conditions to favor these natural processes, as well as in attempts to cultivate specially active strains of the organisms and inoculate roots with them. This side of the problem falls more properly, however, within the province of the Bureau of Plant Industry and the Fixed Nitrogen Research Laboratory has therefore not concerned itself therewith.

There is, however, one aspect of the problem which directly interests this laboratory, and that is the question of the chemical mechanisms by which the organisms effect the fixation. These are of special significance, because aside from the combination with metallic lithium to form nitride, they appear to be the only positively established reactions of free nitrogen which proceed with measurable speed at ordinary temperatures. Could we discover just what class of compounds the bacteria use in thus operating on free nitrogen at these low temperatures, it might be the clue to a whole new chapter of nitrogen fixation on the industrial scale. Studies in this general direction are being undertaken by the laboratory with the cooperation of the Bureau of Plant Industry, but due to the intrinsic difficulty of the subject, the work is apt to go slowly even under the most favorable conditions.

A COMPREHENSIVE SUMMARY.

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